§ 1 – Observational Cosmology – Hot Big Bang

http://www.sr.bham.ac.uk/~smcgee/ObsCosmo/

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Outline

- Reminder:
  - Y3 assessed problem set 1 (Due: Oct 30, 3:30 pm (TSO))
  - Y4 assessment exercise (Due: Dec 13, 3:30 pm (TSO))
- Discussion of Unit 1 topics:
  - Redshift
  - Hubble Expansion
  - Comoving frame/peculiar velocities
  - Isotropy/homogeneity; galaxy distributions; cosmological principle
  - Distance scale / Hubble parameter
  - CMB
  - Nucleosynthesis

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Syllabus and source

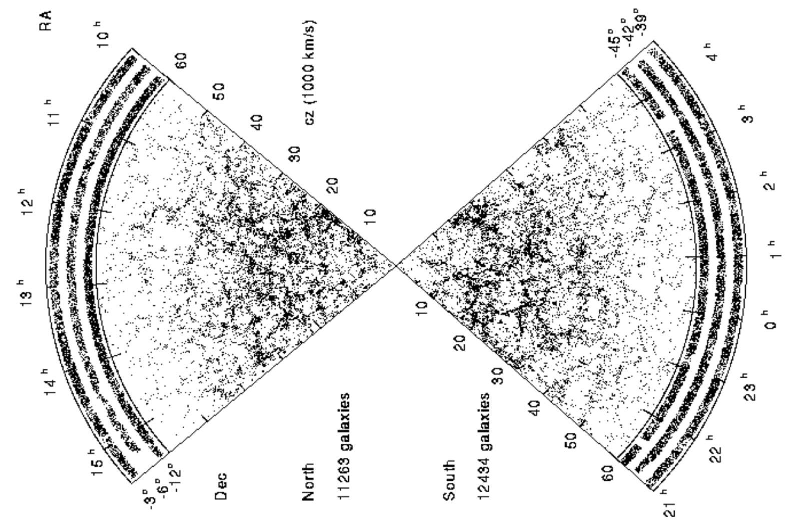
In this unit we will introduce some concepts but mostly we will look at the basic observational evidence supporting the basic Hot Big Bang picture which is now accepted by almost all cosmologists. The three most important planks are the expansion of the universe, the cosmic microwave background, and the evidence from the abundance of the light elements which are believed to have been synthesised in the hot early Universe. I suggest that you research these in the order given below:

Topic	Sources	Comments
Introduction to observations Galaxies, sizes, distances Observations at different wavelengths	L1(2.1 & 2.2) , RR(1.1 to 1.4) L2(2.1 & 2.2)	
Redshift Definition Origins of Doppler shifts	L1(2.4), RR(3.3 & 7.2) L2(2.4)	*More advanced treatments are given in L2(A2.1) and RR(7.4), but you are not yet ready for these.*
Hubble expansion Concept; observations; receding galaxies	L1(2.4), NW(Part 1), RR(3.3) L2(2.4)	
Comoving frame and peculiar velocities Concept of co-movement Galaxy motions ; effect on redshifts	NW(Part 1) , RR(3.3 & 4.1)	
Observed isotropy and homogeneity of the Universe; galaxy distribution; Cosmological Principle Meaning of isotropy & homogeneity Supporting observations Cosmological (Copernican) principle, cosmic time	L1(1 & 2.3), L2(1 & 2.3)RR(3.4, 3.5 & 4.2), NW(Part 1)	*See especially the plot of density fluctuation amplitude againt size scale in NW.*
Distance scale and value of H_0 Methods of measuring distances The distance ladder Best current value of Ho	RR(3.2 & 3.3), NW(Distances)	*The most important methods are: Parallax, Main Sequence fitting, Cepheids and RR-Lyraes, Supernovae, Tully-Fisher*
Cosmic microwave background Observed temperature, isotropy, spectrum Origin & implications Dipole	NW(Part 1), RR(3.4 & 5.5), L1(2.5.2 & 9.1), L2(2.5.2 & 10.1)	*Don't worry too much about microwave background fluctuations at this stage.*
Cosmic nucleosynthesis - the abundance of the light elements See the guidance	L1(11 to 11.2), unit 1 lecture L2(12 to 12.2) MW, RR(5.3), Thuan & Izotov	*Important guidance is given here.* *Note that Fig 11.1 of Liddle(1st edition) has densities on the x-axis in cgs units. This is fixed in the 2nd edition*

Notes

Observational overview

- Observations in visible light:
  - Stars – 10^{30} kg; sourced by nuclear fusion; 1 pc = 3.2 Lyrs
  - Galaxies – 10^{11} stars/solar masses; Milky way – 12.5 kpc in radius; 0.3 kpc high
  - The Local group – LMC, SMC, Andromeda – a few Mpc (1 Mpc = 3.086×10^{22} metres
  - Clusters of galaxies, supercluster, voids – rich structure on the scale of 100 Mpc
  - Smooth on large scales.



Observational overview

- Observations in microwaves – CMB
- Radio Waves – galaxies, AGN, reionization
- Infrared – dust obscured star formation
- X-rays – hot plasmas;
  Galaxy clusters,
  AGN

Cosmological principle

Cosmological principle – We do not occupy a unique position in the Universe.

At each epoch, the universe is the same at all locations and in all directions, except for local irregularities.

The universe is isotropic and homogeneous at any given time, and its dynamics should be the same everywhere.

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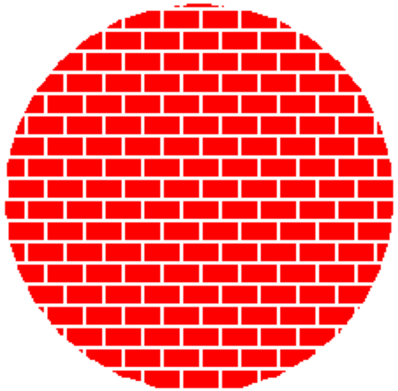
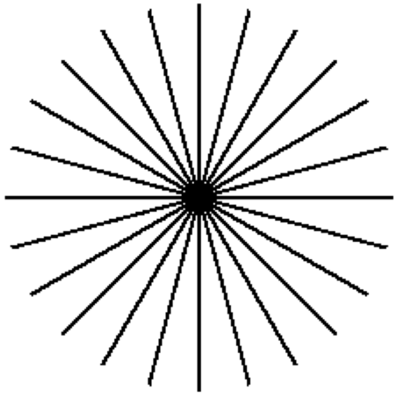
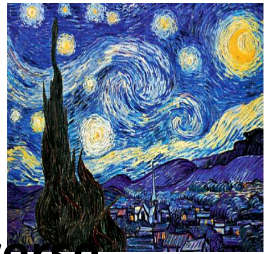
Isotropy – The universe looks the same in all directions.





Cosmological principle



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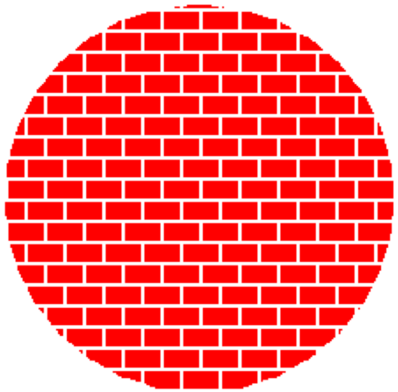
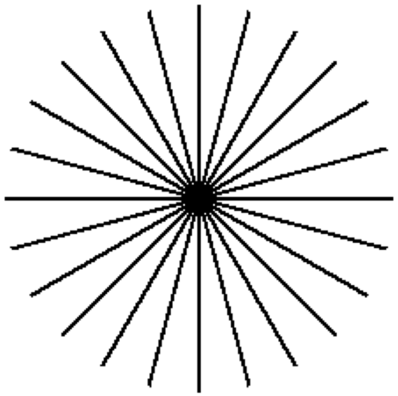


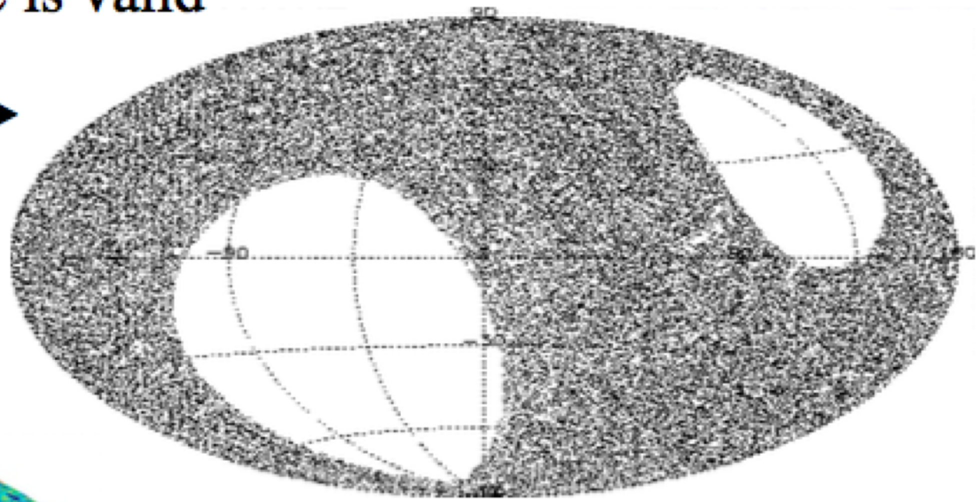


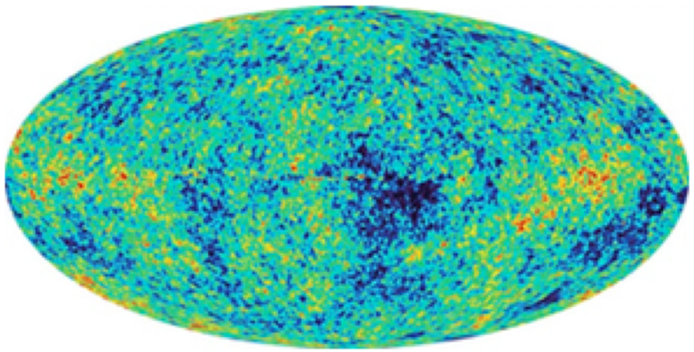
Note: different from Perfect Cosmological Principle, which states the Universe appears the same at all times and is unchanging.

Homogeneous and Isotropric

Globally, on scales larger than ~ 100 Mpc, say, it is - so the cosmological principle is valid

Distribution on the sky → of 65000 distant radio sources from the Texas survey, a cosmological population





… and of course the CMBR, uniform to better than $\Delta T/T < 10^{-5}$, after taking the dipole out

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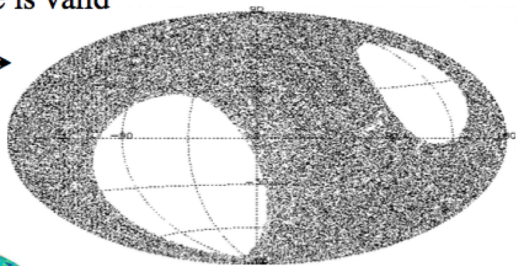

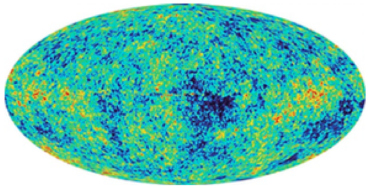

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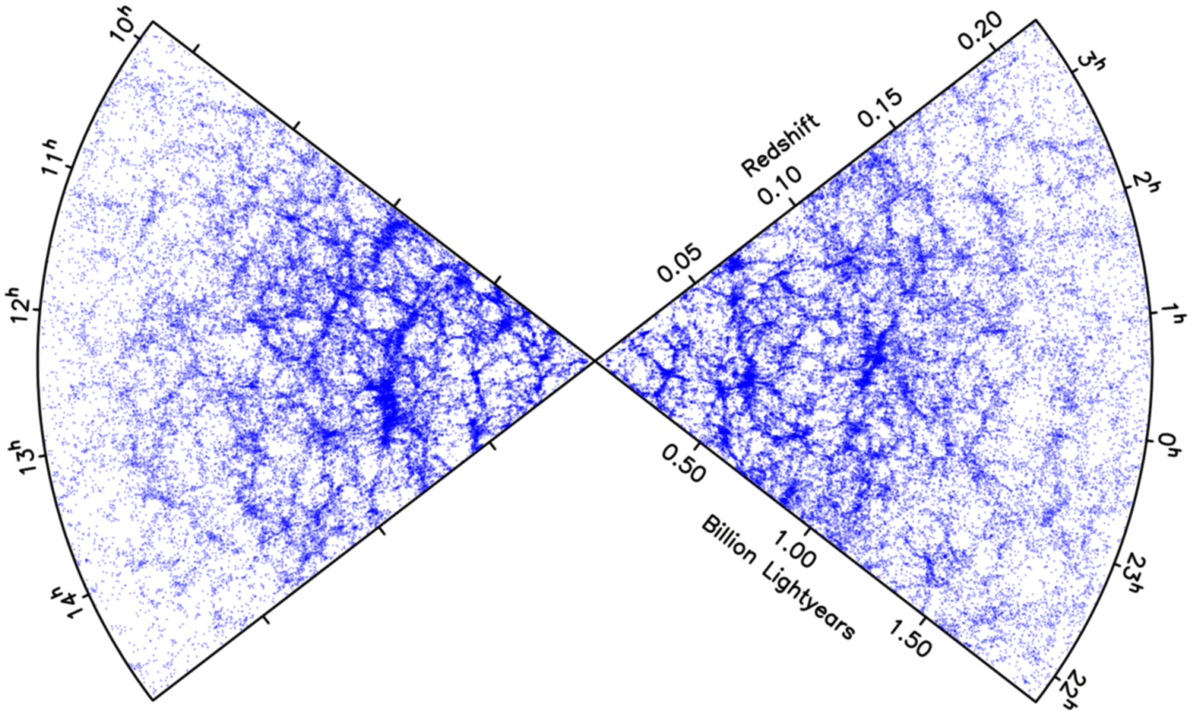
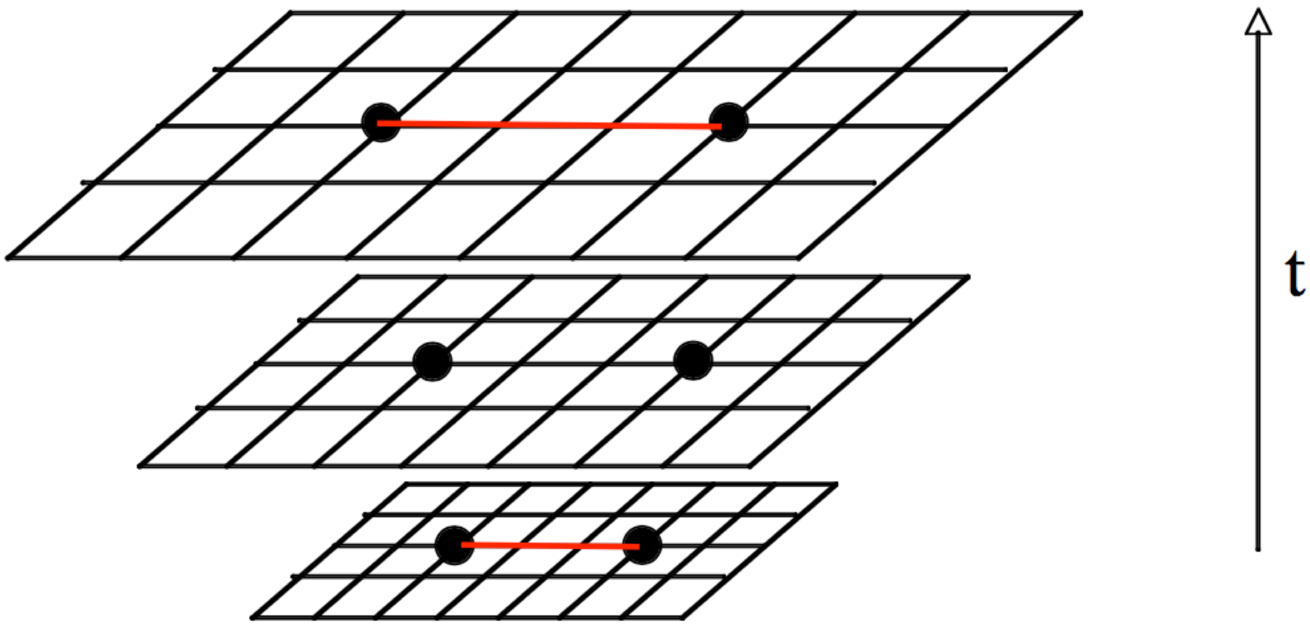


But, this is not true on smaller scales

Distances:
co-moving, physical, scale factor



physical distance

$$r(t) = a(t)x$$

co-moving distance x: distance measured on the grid (always 3 units in this example)

scale factor a(t): size of the grid (varies with time as universe expands)

Luminosity distance

In relativistic cosmologies, observed flux (bolometric, or in a finite bandpass) is:

$$f = L / [(4\pi D^2) (1+z)^2]$$

One factor of $(1+z)$ is due to the energy loss of photons, and one is due to the time dialation of the photon rate.

A **luminosity distance** is defined as $D_L = D (1+z)$, so that $f = L / (4\pi D_L^2)$.

Angular diameter distance

Angular diameter of an object with a fixed ***comoving*** size X is by definition

$$\theta = X / D$$

However, an object with a fixed ***proper*** size X is $(1+z)$ times larger than in the comoving coordinates, so its apparent angular diameter will be

$$\theta = (1+z)\, X / D$$

Thus, we define the **angular diameter distance** $D_A = D / (1+z)$, so that the angular diameter of an object whose size is fixed in proper coordinates is $\theta = X / D_A$

Distances

Distances

With the above definition of the comoving coordinates, the proper distance to an object (measured along a geodesic at time *t*) is simply

$$d_p(t) = a(t) \int_0^r dr = a(t)\, r$$

and for a flat universe (*k*=0) the luminosity distance is $d_L = d_p(t_0)\,(1+z)$

and the angular diameter distance $d_A = d_p(t_0)/(1+z)$.

Redshift

We define **doppler redshift** to be the shift in spectral lines due to motion:

$$z = \frac{\Delta\lambda}{\lambda} = \sqrt{\frac{1 + v/c}{1 - v/c}} - 1$$

which, in the case of **v<<c** reduces to the familiar

$$z = \frac{v}{c}$$

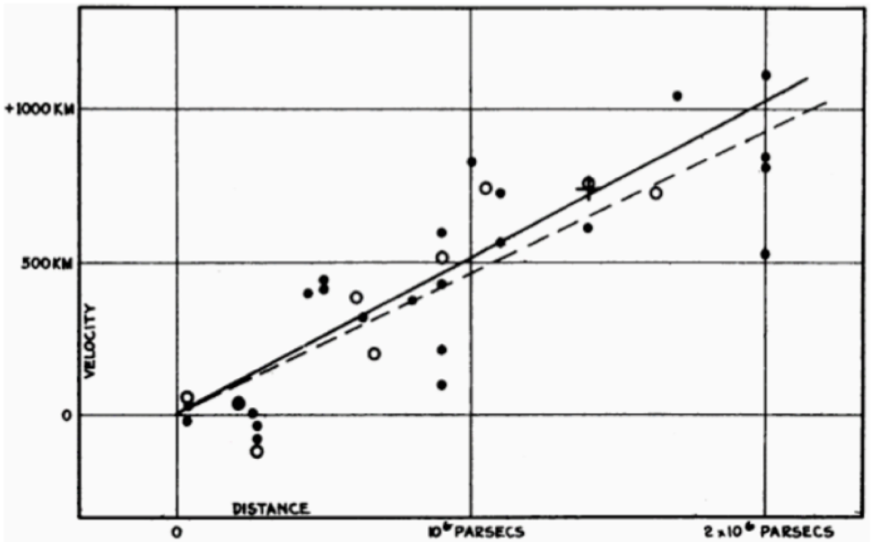


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

Cosmological Redshift

A more correct approach is to note that the wavelengths of photons expand with the universe:

$$\frac{R(t_0)}{R(t_e)} = \frac{\lambda_0}{\lambda_e}$$

Or, by our definition of redshift:

$$z = \frac{\Delta\lambda}{\lambda}$$

We get:

$$\boxed{\frac{R(t_0)}{R(t_e)} = (1 + z)}$$

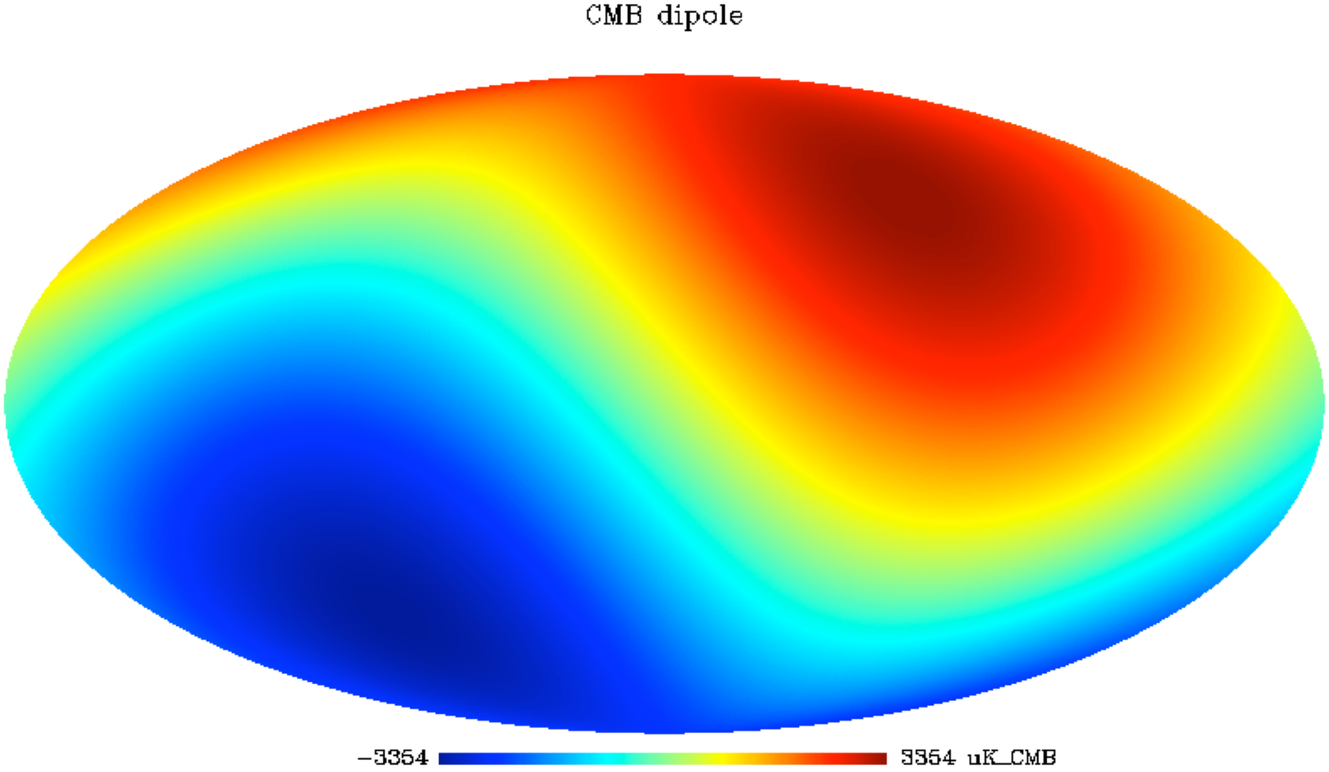
The two approaches are actually equivalent

Comoving frame and peculiar velocities

Hubble law defines a frame of reference

Being at rest in this frame is said to be 'comoving'

We have a peculiar velocity of ~ 350 km/s



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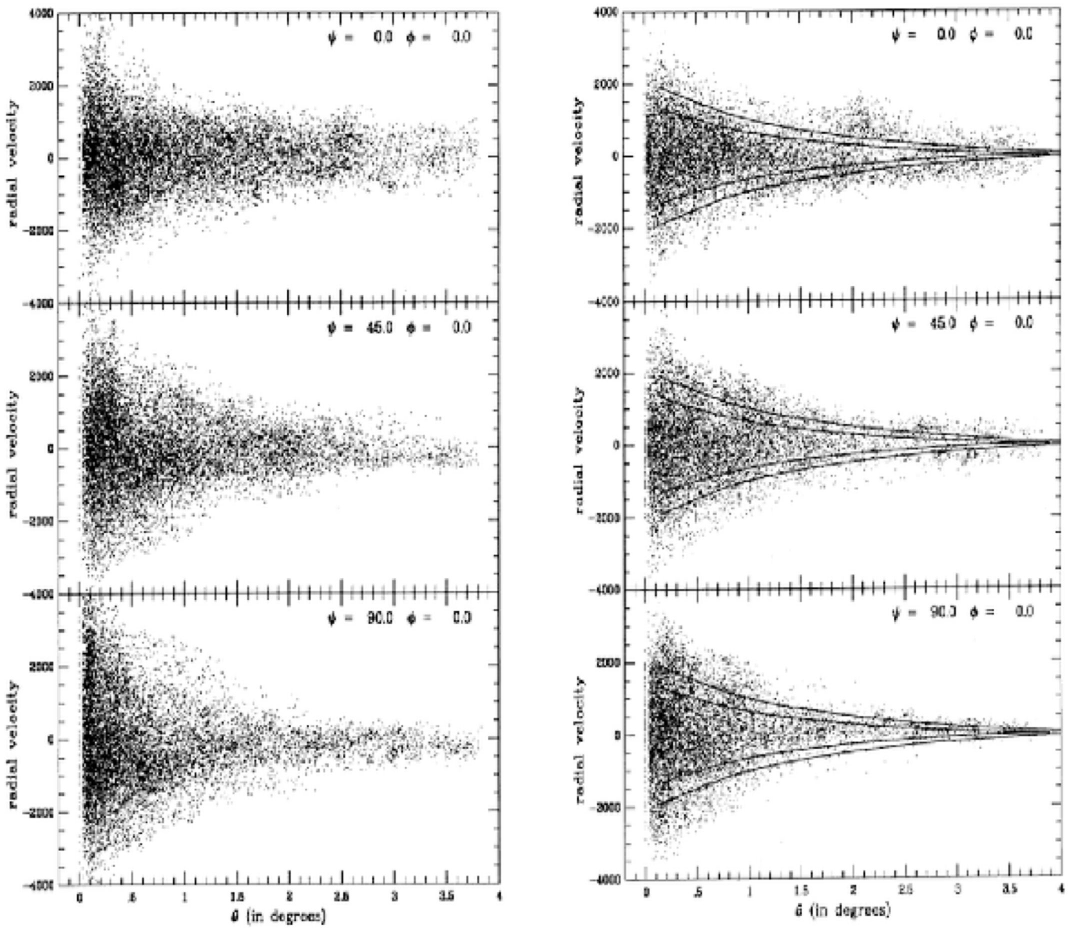
Velocity = H*x + peculiar velocity



Distance scale and H_0

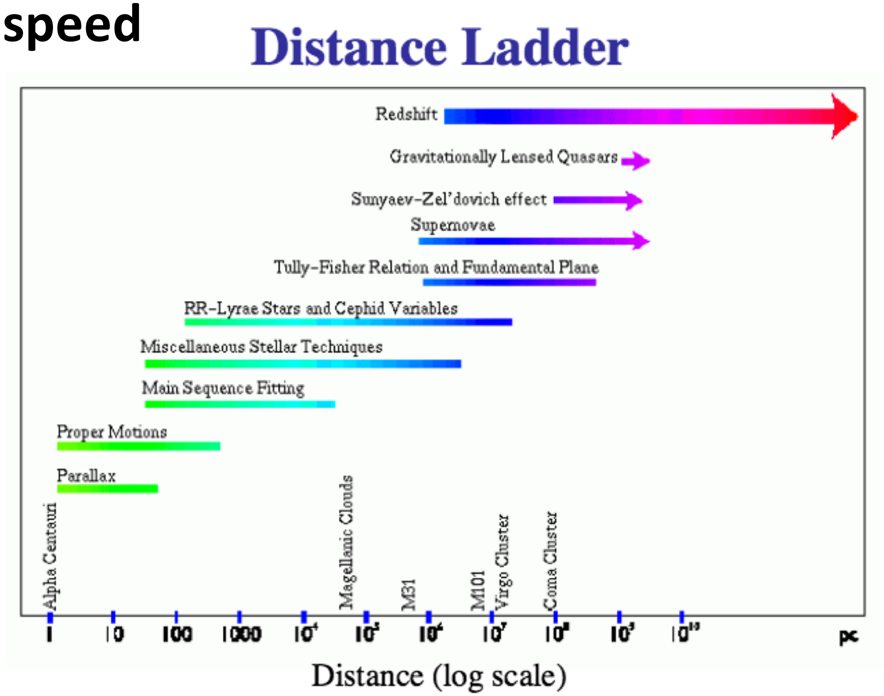
Parallax – only model independent method

Cepheids – evolved high-mass stars on the instability strip in H-R diagram

RR Lyrae Stars – evolved old, low mass, low metallicity stars – short periods

Supernovae – intrinsic brightness known – Ia (binary WD detonating)

Tully-Fisher – luminosity related to rotation speed



Cosmic microwave background

$$T_0 = 2.725 \pm 0.001 \text{ Kelvin}$$